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TIDAL TORQUES AND THE ORIENTATION OF NEARBY DISK GALAXIES

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ABSTRACT

We use numerical simulations to investigate the orientation of the angular momentum axis of disk galaxies relative to their surrounding large scale structure. We find that this is closely related to the spatial configuration at turnaround of the material destined to form the galaxy, which is often part of a coherent two-dimensional slab criss-crossed by filaments. The rotation axis is found to align very well with the intermediate principal axis of the inertia momentum tensor at this time. This orientation is approximately preserved during the ensuing collapse, so that the rotation axis of the resulting disk ends up lying on the plane traced by the protogalactic material at turnaround. This suggests a tendency for disks to align themselves so that their rotation axis is perpendicular to the minor axis of the structure defined by surrounding matter. One example of this trend is provided by our own Galaxy, where the Galactic plane is almost at right angles with the supergalactic plane (SGP) drawn by nearby galaxies; indeed, the SGP latitude of the North Galactic Pole is just 6 degrees. We have searched for a similar signature in catalogs of nearby disk galaxies, and find a significant excess of edge-on spirals (for which the orientation of the disk rotation axis may be determined unambiguously) highly inclined relative to the SGP. This result supports the view that disk galaxies acquire their angular momentum as a consequence of early tidal torques acting during the expansion phase of the protogalactic material.

Subject headings: Galaxy: disk, structure, formation

1. INTRODUCTION

In hierarchical models of galaxy formation, the origin of galactic angular momentum is ascribed to tidal torques operating early on the material destined to form a galaxy. Over the years, starting from the ideas of Stromberg (1934) and Hoyle (1949), and quantified by the work of Peebles (1969), Doroshkevich (1970), and White (1984), a number of important properties inherent to the acquisition of angular momentum through tidal torques (hereafter referred to, for short, as "tidal torque theory", or TTT) have been identified.

The efficiency of the torquing is low, typically endowing galactic material with a rather small amount of net rotation. This implies that large collapse factors within massive dark matter halos are needed to explain the centrifugally-supported nature of galactic disks (Fall & Efstathiou 1980). To leading order, galaxy spins result from the misalignment between the principal axes of the inertia momentum tensor ($\mathbf{I}_{ij}$) of the material being torqued and of the "shear" tensor ($\mathbf{T}_{ij} = -\partial^2\phi/\partial x_i \partial x_j$) generated by external material. In the Cartesian principal axis frame of the protogalaxy, the leading term of the torque is given by $\tau_i = dL_i/dt \approx T_{jk}(I_{jj} - I_{kk})$ (here i, j, and k are cyclic permutations of 1 to 3, and L_i are the cartesian components of the angular momentum). The inertia term is maximal along the direction that maximizes the difference between I_{jj} and I_{kk}; i.e., the *intermediate* axis of inertia. Angular momentum growth is typically linear with time at early times (since $\Omega \approx 1$ then) and effectively ends at turnaround, when $\mathbf{I}$ is maximal. In general, then, the direction of the angular momentum will be determined by the *shape* of the protogalactic material at turnaround, and is expected to align with the intermediate axis of inertia if $\mathbf{T}$ and $\mathbf{I}$ are uncorrelated.

Many of these expectations have been confirmed by a number of studies of the angular momentum properties of dark matter halos formed in cosmological simulations (see, e.g., Barnes & Efstathiou 1987, as well as the more recent work of Porciani, Dekel & Hoffman 2002a,b, and references therein). The latter authors point out that $\mathbf{T}$ and $\mathbf{I}$ are, in fact, highly correlated, and conclude that, relative to the principal axes of $\mathbf{T}$, the most significant trend is for the spin to be perpendicular to the direction of maximum compression (i.e., that of the minimum eigenvector of $\mathbf{T}$). Because $\mathbf{T}$ and $\mathbf{I}$ are correlated, the direction of maximum compresion roughly coincides with the direction of the minor axis of inertia at the time of turnaround. A solid prediction of TTT is, therefore, that galaxy spins should be nearly perpendicular to the minor axis of the collapsing material at late times.

The main shortcoming of this work is that it applies mainly to dark halos, rather than to the luminous (observable) component of galaxies. Simulations that include the presence of a dissipative gaseous component have highlighted the possibility that large losses of angular momentum may accompany the collapse of the baryonic component (Navarro & Benz 1991, Navarro & White 1994,

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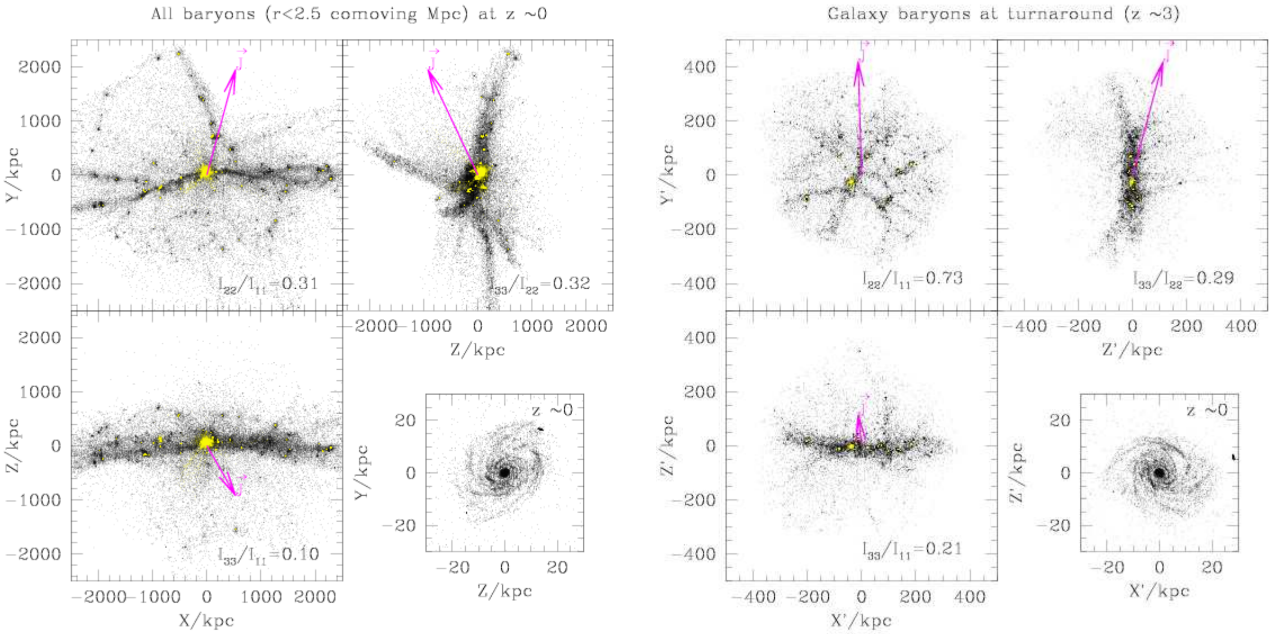

FIG. 1.— (*a-left*) Spatial distribution of all baryons in the resimulated high-resolution region at late times. Three orthogonal projections are shown, aligned with the principal axis of inertia of the system at that time. Units are in physical kpc. Particles in yellow are stars; others are gas. Labels in each panel indicate the aspect ratio of the system. Arrows indicate the relative importance of the cartesian components of the angular momentum. Bottom-right panel is a zoom of the Y-Z projection that shows the gaseous disk almost face-on, implying that its rotation axis lies on the plane of the surrounding structure. (*b-right*) Same as (a) but for the baryons that will collapse to form the galaxy at $z = 0$, shown at turnaround in its own principal axis frame. The bottom-right panel shows a zoomed-in (X', Z') projection of the same baryons at $z \sim 0$, which have collapsed to form a disk whose rotation axis remains closely aligned to the intermediate (Y') axis at turnaround.

Navarro & Steinmetz 1997). The rather indirect mapping between the angular momentum of dark halos and that of their baryonic components makes it difficult to assess the success of TTT in accounting for the spin of spiral galaxies. The discussion of the previous paragraphs, however, suggests that TTT may be tested by looking for residual correlations originating from the coupling between the shear and inertia momentum tensors that dominates the angular momentum growth in protogalaxies. One example of this is the recent work of Lee & Pen (2000, 2001, 2002, see also Lee, Pen & Seljak 2000), who attempt to reconstruct the shear field from the observed galaxy spin fields and to uncover correlations between the spin field and the large-scale distribution of matter.

We investigate here a related signature expected from TTT; i.e., the correlation between the "shape" of protogalactic matter distribution at turnaround and the direction of the resulting angular momentum. As explained above, TTT suggests a trend for spin axes to be perpendicular to the minor axis of the sheet, so that disk galaxies should be highly inclined relative to the plane defined by their surrounding structure.

In this *Letter* we explore whether disk galaxies assembled hierarchically in ΛCDM numerical simulations indeed follow these expectations. In addition, we search for a statistical signature of the predicted trend in catalogs of nearby galaxies.

2. NUMERICAL EXPERIMENTS AND RESULTS

We have analyzed four N-body/gasdynamical simulations of the formation of disk galaxies in the "concordance" ΛCDM cosmogony ($\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.65$, $\Omega_b = 0.019\, h^{-2}$, $\sigma_8 = 0.9$). These simulations are similar to those described in detail by Abadi et al (2003a,b) and Meza et al (2003), where we refer the reader for full details. The simulations follow self-consistently the evolution of a small region surrounding a target galaxy, excised from a large periodic box and resimulated at higher resolution preserving the tidal fields from the whole box. For the purposes of the discussion here all four simulations give consistent results. We have chosen to illustrate these using the simulation presented by Abadi et al (2003a,b), but will use the others to verify the general applicability of our results.

Figure 1a shows, at late times ($z \sim 0$), the baryons within ~ 2.5 Mpc of the target galaxy. The three different projections in the figure have been chosen so as to coincide with the principal axes of the inertia momentum tensor. This figure shows the high degree of anisotropy that characterizes the non-linear evolution of structures in a ΛCDM universe. What started off as a roughly spherical region ~ 5 comoving Mpc across develops into a coherent triaxial structure that surrounds the target galaxy (located at the center of the panels in Figure 1a). The minor axis of the structure, in particular, is very stable across the structure, which may thus be described as a "sheet" criss-crossed by filaments. The ratios of the inertia tensor eigenvectors are given in Figure 1a, and are not dissimilar to the mean of all four systems: $\langle I_{22}/I_{11}\rangle = 0.419$ (with dispersion $\sigma = 0.360$), $\langle I_{33}/I_{11}\rangle = 0.174$ ($\sigma = 0.157$) and $\langle I_{33}/I_{22}\rangle = 0.408$ ($\sigma = 0.059$).

The arrows in the panels of Figure 1a indicate the relative magnitude of the cartesian components of the angular momentum of the sheet, and illustrate the TTT pre-

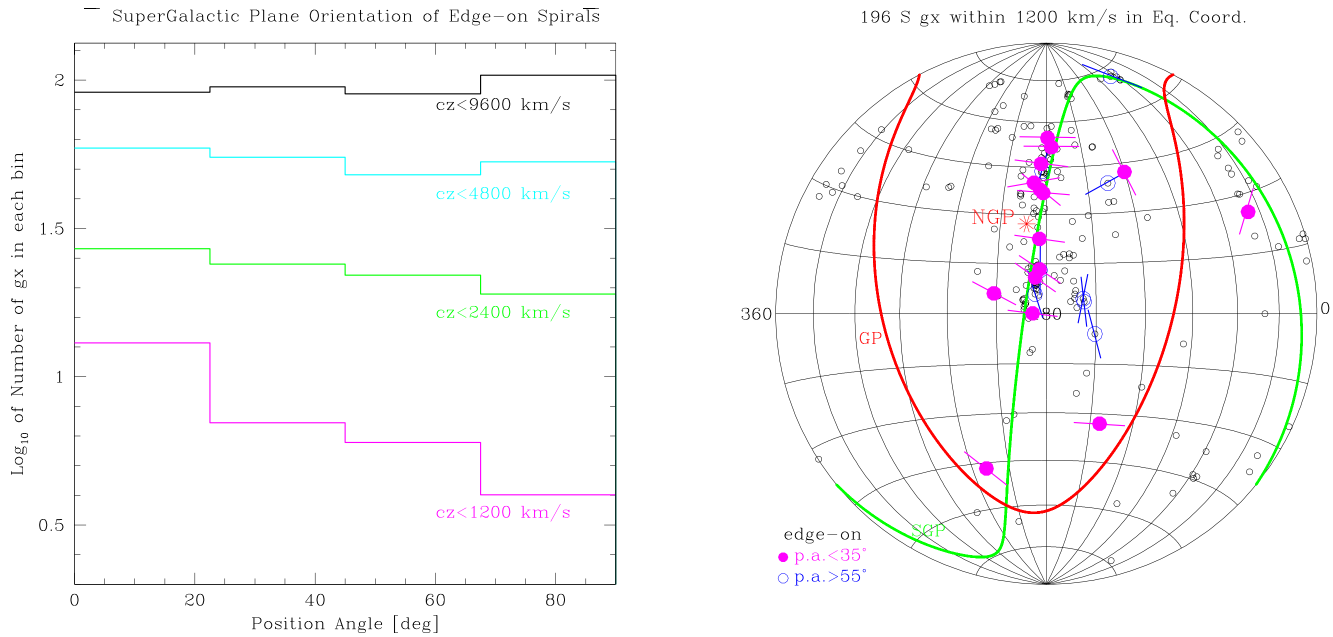

FIG. 2.— (*a- left*) Histogram of supergalactic position angles of edge-on ($b/a < 0.175$) spirals in the Principal Galaxy Catalog (PGC, Paturel et al 1997) selected within various recession velocity limits, as labelled. A position angle of 0° means that the galaxy's plane is *perpendicular* to the SGP; 90° means that it is *parallel* to the SGP. There is a well-defined excess of spirals perpendicular to the SGP in the vicinity of the Milky Way. (*b-right*) Aitoff equatorial projection of all spirals within 1200 km s^{-1} in the PGC. The U-shaped thick curve is the Galactic plane (GP); the S-shaped curve is the SGP. The projected major axis of edge-on spirals is shown for galaxies with position angles smaller than 35° (filled circles) and greater than 55° (open circles).

dicted trend (see §1) for spins to be approximately perpendicular to the direction of maximum compression or, roughly, to that of the minor axis (Z) during the non-linear stages of the evolution. Indeed, the whole sheet of material is slowly spinning around the *intermediate* principal axis of inertia (i.e., $|L_Y| \gg |L_X|, |L_Z|$). This is a generic result of our four simulations; quantitatively, we find that the angular momentum of the high-resolution region surrounding the target galaxies to be oriented such that $\langle |L_X|/|\vec{L}|\rangle = 0.255$ ($\sigma = 0.104$), $\langle |L_Y|/|\vec{L}|\rangle = 0.860$ ($\sigma = 0.103$), and $\langle |L_Z|/|\vec{L}|\rangle = 0.351$ ($\sigma = 0.275$).

This two-dimensional structure is present since early times and, at $z \sim 3$, its minor axis is approximately parallel to that of the material that will collapse to form the target galaxy at $z = 0$ (i.e., the "protogalaxy", see Figure 1b, as well as Sugerman, Summers & Kamionkowski 2000 for a similar analysis). The shape of the protogalactic material at turnaround [5] is indicated in the the panels of Figure 1b; for the four simulations we find $\langle I_{22}/I_{11}\rangle = 0.652$ (with dispersion $\sigma = 0.0.247$), $\langle I_{33}/I_{11}\rangle = 0.265$ ($\sigma = 0.095$) and $\langle I_{33}/I_{22}\rangle = 0.429$ ($\sigma = 0.132$). The angular momentum of the protogalaxy at $z \sim 3$ shows similar alignment properties to that of its surrounding material at $z \sim 0$; in particular, the close alignment with the intermediate inertia axis at turnaround is well defined in all four simulations: $\langle |L_{X'}|/|\vec{L}|\rangle = 0.055$ ($\sigma = 0.031$), $\langle |L_{Y'}|/|\vec{L}|\rangle = 0.832$ ($\sigma = 0.260$), and $\langle |L_{Z'}|/|\vec{L}|\rangle = 0.421$ ($\sigma = 0.319$).

The angular momentum direction of the baryons at turnaround is approximately preserved by the disk component at $z = 0$ and, as a result, the plane of the disk is highly inclined relative to the plane defined by its surrounding large-scale structure. This is illustrated in the bottom right panels of Figures 1a and 1b, where the disk at $z = 0$ is seen approximately face-on in projections that contain either the minor axis of the surrounding structure at $z \sim 0$ or that of the protogalaxy at turnaround. This indicates that the shape of the protogalactic material during the expansion phase effectively determines the orientation of the spin axis of the resulting galaxy. Since these anisotropies correlate across a wide range of scales in ΛCDM, a signature of this process might be preserved as a residual alignment between the disk and its surroundings; the rotation axis of disk galaxies may be expected to lie *on* the plane defined by its surrounding structure. We explore next whether such alignments are indeed present in samples of disk galaxies in the nearby Universe.

3. ORIENTATION OF NEARBY DISK GALAXIES

As recognized by de Vaucouleurs (1953) in the Shapley-Ames catalog, galaxies in the vicinity of the Milky Way are arranged in a two-dimensional slab usually referred to as the "super galactic plane" (SGP). This structure stands out clearly in whole-sky catalogs of nearby galaxies; extends out to several tens of Mpc from the Galaxy; and includes many of the major features of the local large scale distribution of matter, such as the Virgo cluster, the Perseus-Pisces supercluster, and the Great Attractor (Lahav et al 2000).

The plane of the Galaxy is highly inclined relative to the SGP; indeed, the two planes are approximately perpendicular to each other, as indicated by the low supergalactic latitude of the North Galactic Pole (∼ 6°). This situation is similar to that of the simulated disk galaxy in relation

[5] We define as turnaround the time when the moment of inertia of the protogalaxy attains its maximum.

to its surrounding structure, as discussed in §2. It is therefore tempting to regard the rather peculiar orientation of the Galactic plane relative to the SGP as a result of early torques acting during the protogalactic stage.

If this interpretation is correct, we would expect an excess of nearby galaxies whose rotation axes are approximately perpendicular to the normal to the SGP. The existence of such alignment has proven controversial; prior work has led to claims of statistical evidence for such "anti-alignment" of galactic planes relative to the SGP (see, e.g., Flin & Godlowski 1989 and references therein), but also to suggestions that there is no convincing evidence for deviations from a random distribution of orientations (see, e.g., Dekel 1985)

A number of factors complicate this analysis and may explain this disagreement. For example, the statistics of the position angles of galaxy samples that do not discriminate properly between elliptical and disk galaxies may be inconclusive, as the projected major axis of early type galaxies—in contrast to those of disks—may bear little relation to the angular momentum of the galaxy. In addition, determining the direction of the rotation axis of a spiral galaxy requires knowledge not only of the position angle and inclination (readily available in most catalogs), but also of *how* the galaxy is inclined on the sky, i.e., which side of the galaxy is closer to the observer. This is known for a few well-studied spirals, such as M31 [6] , but it is generally unavailable for most galaxies. The uncertainty introduced by this ambiguity depends on inclination: it is maximal for galaxies inclined by 45 degrees, but is negligible for galaxies seen either face-on or edge-on. In this *Letter* we restrict our analysis to edge-on spirals and search for a possible correlation between the orientation of galaxy disks and the SGP. We explore ways of circumventing the aforementioned ambiguity and extend this analysis to all nearby spirals in a forthcoming paper.

Figure 2a shows the distribution of position angles (in the supergalactic reference frame) of all edge-on [7] nearby spiral galaxies in the Principal Galaxy Catalog (PGC) with recession velocities within various limits. Since we are only interested in the direction of the rotation axis relative to the SGP, we have reduced all position angles to between 0° and 90°. As shown in Figure 2a, there is a clear excess of nearby edge-on galaxies highly inclined relative to the SGP. The significance of the excess decreases the larger the volume considered around the Milky Way. Within 1200 km s^{-1} there are 196 spirals in the PGC with measured inclinations and position angles. Of these ~ 30 are edge-on. Figure 2a shows that roughly three times as many edge-on galaxies with position angles between 0° and 20° as in the range (70°, 90°); a simple KS test shows that this excess is significant to the 92% level. The magnitude of the excess (and its significance) decreases to $\sim 40\%$ for spirals with recession velocities under 2400 km s^{-1}, and is essentially negligible when galaxies within 5000 km s^{-1} (or greater) are considered.

This result supports the tendency of spirals to be highly inclined relative to the SGP claimed by Flin & Godlowski (1989). Our study provides a compelling physical interpretation for the origin of such alignment and supports the view that the angular momentum of spiral galaxies originates in tidal torques tightly coupled to anisotropies during the expansion, turnaround, and collapse of protogalactic material.

4. SUMMARY AND DISCUSSION

We have used cosmological N-body/gasdynamical simulations to study the orientation of disk galaxies relative to their surrounding structure. We find that the angular momentum axis of simulated galaxies is perpendicular to the minor axis (and very well aligned with the *intermediate* axis) of the material destined to form the galaxy at turnaround, which is usually arranged on a two-dimensional slab criss-crossed by filaments. These sheet-like structures may extend out to several Mpc, in a way reminiscent of the "supergalactic plane" that surrounds the Milky Way. This coherence over a wide range of scales in the anisotropies present during the expansion and turnaround of protogalactic material generally results in galaxy disks highly inclined relative to the large-scale two-dimensional structure where they are embedded.

This provides a natural explanation for the high inclination of the Milky Way relative to the supergalactic plane, as well as for the excess of nearby edge-on spirals whose rotation axes lie approximately *on* the supergalactic plane. It may also offer a physical interpretation for the tendency of satellite galaxies to align along the minor axis of bright spirals (the "Holmberg effect"). Our interpretation offers as well a number of "natural" predictions that may be used to falsify it. In particular, we expect an excess of highly inclined spirals in *any* two-dimensional large-scale distribution of galaxies, a result that may have already been detected in the Perseus supercluster (Flin 1988), and that could be verified in large galaxy surveys such as the 2dfGRS and the SDSS. The detection of these and other non-trivial correlations between the spin and matter fields would serve to establish beyond doubt the validity of tidal torque theory as the origin of the angular momentum of spiral galaxies.

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REFERENCES

Abadi, M. G. et al 2003, ApJ, 591, 499
Abadi, M. G. et al 2003, ApJ, 597, 21
Barnes, J. & Efstathiou, G. 1987, ApJ, 319, 575
Dekel, A. 1985, ApJ, 298, 461
Doroshkevich A. G., 1970, Astrofiz., 6 581
Flin, P. & Godlowski, W. 1989, ASSL Vol. 155: Astronomy, Cosmology and Fundamental Physics, 418
Hoyle, F., 1949, in Problems of Cosmical Aerodynamics (Dayton, Ohio: Central Air Documents Office), p.195. ApJ, 532, L5
Lee, J. & Pen, U. 2000, ApJ, 532, L5
Lee, J. & Pen, U. 2001, ApJ, 555, 106
Lee, J. & Pen, U. 2002, ApJ, 567, L111
Meza, A. et al 2003, ApJ, 590, 619
Paturel, G., et al. 1997, A&AS, 124, 109

[6] The Andromeda galaxy is only mildly inclined relative to the SGP—the supergalactic latitude of M31's pole is ~ 56 degrees.

[7] We consider a spiral galaxy edge-on if the ratio of semiminor to semimajor axis is less than 0.175.

Peebles, P. J. E. 1969, ApJ, 155, 393
Pen, U., Lee, J., & Seljak, U. 2000, ApJ, 543, L107
Porciani, C., Dekel, A., & Hoffman, Y. 2002, MNRAS, 332, 325
Porciani, C., Dekel, A., & Hoffman, Y. 2002, MNRAS, 332, 339
Strömberg, G. 1934, ApJ, 79, 460
Sugerman, B. et al 2000, MNRAS, 311, 762
Thacker, R. J. & Couchman, H. M. P. 2001, ApJ, 555, L17
White, S. D. M. 1984, ApJ, 286, 38